AFRL-SN-WP-TM-2005-1136

TUNABLE SOLID-STATE MID-IR LASER ENGINEERING

Kenneth L. Schepler

Electro-Optical (EO) Countermeasures Technology Branch (AFRL/SNJW)
Electro-Optical Sensor Technology Division
Sensors Directorate
Air Force Research Laboratory, Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7320

JULY 2005

Final Report for 01 October 1994 – 28 July 2005

Approved for public release; distribution is unlimited.

STINFO FINAL REPORT

SENSORS DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7320

NOTICE

PAO Case Number: AFRL/WS-05-1684, 18 Jul 2005.

THIS TECHNICAL REPORT IS APPROVED FOR PUBLICATION.

/s/
____
KENNETH L. SCHEPLER
Principal Scientist
EOCM Technology Branch

/s/
____
JOSEPH R. KOESTERS, Chief
EOCM Technology Branch
EO Sensors Technology Division

/s/
____
KEVIN J. McCAMEY, Acting Chief
EO Sensors Technology Division
Sensors Directorate

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
July 2005	Final	10/01/1994 – 07/28/2005

4. TITLE AND SUBTITLE
TUNABLE SOLID-STATE MID-IR LASER ENGINEERING

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
61102F/62204F

6. AUTHOR(S)
Kenneth L. Schepler

5d. PROJECT NUMBER
2301/2001

5e. TASK NUMBER
EL/05

5f. WORK UNIT NUMBER
01/13

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Electro-Optical (EO) Countermeasures Technology Branch (AFRL/SNJW)
Electro-Optical Sensor Technology Division
Sensors Directorate
Air Force Research Laboratory, Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7320

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-SN-WP-TM-2005-1136

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Sensors Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson AFB, OH 45433-7320

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/SNJW

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-SN-WP-TM-2005-1136

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
This report contains the in-house work performed under the combined funding of two work units: 2301EL01 and 20010513.

14. ABSTRACT
This report describes in-house efforts to develop advanced tunable mid-IR laser materials and nonlinear frequency conversion techniques useful for IRCM and laser radar sources. We developed a new class of laser materials, Cr2+doped II-VI materials, with broadband tunability in the 2-3 micron region with room temperature operation and 4.2-W output. We fabricated periodically poled ferroelectric materials and demonstrated broadband tuning and narrowband seeding. We demonstrated pulse energies of 60mJ from a stack of periodically poled lithium niobate wafers. Other patterned nonlinear materials such as orientation patterned GaAs were characterized and show great promise for tuning throughout the 1.5-14 micron region.

15. SUBJECT TERMS
Lasers, Cr^{2+} laser, infrared, nonlinear frequency conversion, quasi-phasematching, periodically poled lithium niobate, orientation patterned GaAs

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			Kenneth L. Schepler
Unclassified	Unclassified	Unclassified	SAR	18	19b. TELEPHONE NUMBER *(Include Area Code)* (937) 904-9661

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

TABLE OF CONTENTS

ACKNOWLEDGMENTS

The author gratefully acknowledges funding for this research from the Air Force Office of Scientific Research (AFOSR), and the Air Force Research Laboratory Sensors Directorate (AFRL/SN).

I also gratefully acknowledge the advisors and graduate students who made so many of our exciting discoveries.

Staff and Advisors

Dr Rita Peterson	AFRL
Prof Peter Powers	The University of Dayton
Prof Won Roh	Air Force Institute of Technology
Prof Vince Dominic	The University of Dayton
Dr Shrikrishna Hegde	University of Dayton Research Institute
Dr Larry Myers	AFRL
Capt Dale Fenimore	AFRL
Dr Robert Eckardt	AFRL IPA
Dr Mark Dubinskii	NRC Research Associate
Dr Stefan Kück	NRC Research Associate
Prof Venkat Gopalan	NRC Summer Faculty

Students

Dr Mark Missey
Dr Ned O'Brien
Capt Stephen Russell, PhD
1Lt Frank Glavic
Ms Debra Krause
Mr Leo Gonzalez
Capt Jason McKay, PhD
Mr Sean Kelley
Major Monte Turner, PhD
Capt Bryce Schumm
Capt Mike Harm
Mr Eric Vershure
Mr Patrick Berry
Capt Daren Chauvin
Mr James Alverson
Capt Joshua Meyer

1. INTRODUCTION

This technical report describes the results of two in-house workunits combined technically and financially. For this reason a single final report is being written for both workunits.

Workunit 2301EL01 is a 6.1 basic research AFOSR-funded effort started in 1994. This workunit was primarily set up to advance the basic laser materials and novel concepts needed for laser source applications, particularly infrared countermeasures (IRCM), although the results found application in laser radar and remotes sensing as well. Emphasis was placed upon tunable mid-IR solid-state technology with extensive tunability and high power, IRCM requirements. Optical spectroscopy, laser device performance, and frequency conversion device performance were used to assess the feasibility of new basic concepts and to investigate new materials.

Workunit 20010513, a 6.2 applied research AFRL-funded effort, was started in 1996 with the objective to obtain improved performance from existing lasers and to demonstrate new concepts which address AF mission requirements. More specifically, we planned demonstrations of improved laser performance, preferably tunable or multiple lines in the ultraviolet, visible, near-IR and mid-IR wavelength regions. . Areas of investigation included tunable solid-state laser devices, nonlinear optical frequency conversion processes, and solid-state excitation mechanisms. This workunit applied the 6.1 basic research of Workunit 2301EL01 to practical military applications.

2. TECHNICAL ACCOMPLISHMENTS

Over the years the specific laser materials, nonlinear materials, and new techniques under investigation gradually evolved to new (and better) materials and techniques but the overall objectives remained much the same. This effort concentrated on means to achieve efficient and tunable lasing with solid-state lasers. Initially, UV to IR wavelengths were of interest but the bulk of the work later moved to the mid-IR, i.e. the 1.5-5 μm spectral region of interest for infrared countermeasures and eyesafe laser radar.

2.1 UV Laser Research

Some early efforts to demonstrate tunable ultraviolet laser output were done in the mid-1990's. Ce^{3+}-doped fluorides were shown to be tunable over the 280-300 nm range and injection seeding allowed both narrow bandwidth and high conversion efficiency. But Air Force application interest in UV radiation waned shortly thereafter. However, such a laser now has renewed interest for biosensing applications.

2.2 Mid-IR Laser Research

Infrared laser material development has included spectroscopic investigations of the lasing potential of Cr^{4+}, Mn^{3+} and Mn^{5+} ions in low crystal field hosts. However, excited state absorption was usually found to limit laser operation to small spectral regions or none at all.

We spent considerable effort developing a high-power Tm,Ho:YLF laser. Initial operation at 5.2 W with 50-ns Q-switched pulses at 5 kHz was demonstrated using liquid nitrogen cooling and diode pumping. Such a laser was ideal for testing the performance of infrared nonlinear frequency conversion materials. Later improvements included fiber coupled diodes for much simpler alignment and closed cycle cooling to eliminate the need to dash for more liquid nitrogen to refill the dewar after each hour of operation. This laser design has run at >15 W cw or Q-switched for hours unattended. It became our workhorse 2-μm pumping laser for investigation of other laser and nonlinear materials.

While Tm,Ho:YLF operates in the mid-IR at 2.06 μm [or 1.88 μm if we use Tm:YLF] it is not broadly tunable so we have sought laser and nonlinear materials to better cover the mid-IR spectrum. Cr^{2+}-doped II-VI semiconductors were first suggested by researchers at Lawrence Livermore National Labs. Our initial work concentrated on development of Cr^{2+}:CdSe. We demonstrated the first lasing in this material and showed that it could operate at room temperature and has a very broad tuning range of 2300-3400 nm. However, we switched to ZnSe as the host material to achieve higher output power because of its high thermal conductivity. We demonstrated 4.2 W of average output power operating at 10 kHz using a thin disk to minimize radial thermal gradients and multi-pass pumping with the Tm,Ho:YLF laser. Most recently, we demonstrated a fiber laser pumped Cr^{2+}:ZnSe laser, a much simpler pumping system than the cryo-cooled Tm,Ho:YLF laser used previously. A new design using doublesided cooling with undoped ZnSe windows was also assembled to show good Cr^{2+}:ZnSe laser operation with easy assembly and disassembly.

At high-power operation even our thin disk design showed significant thermal lensing. We used finite element analysis to calculate the expected thermal lensing effect and measured it independently via an interferometric technique. Modeling and measurement agreed quite well so we now understand the nature and magnitude of thermal lensing present and have proposed designs to mitigate it. This type of laser when combined with an OPO (optical parametric oscillator) frequency converter is of interest for IRCM and remote sensing applications.

2.3 Mid-IR Nonlinear Materials Research

Efforts at the beginning of this program concentrated on characterizing the optical properties of then novel materials such as the KTP (potassium titanyl phosphate) isomorphs RTA (rubidium titanyl arsenate) and KTA (potassium titanyl arsenate) and chalcopyrite isomorphs such as $AgGaSe_2$ and $ZnGeP_2$. Measurements of refractive index for frequency tuning of laser devices, thermal lensing, and measurements of damage threshold were helpful to systems designers. In fact, the low damage threshold of $AgGaSe_2$ led us to investigate the feasibility of using a modelocked pump laser and synchronously pumping an $AgGaSe_2$ OPO, a way to achieve high nonlinear gain without damaging the nonlinear crystal. We demonstrated cw-pumped all-solid-state Tm^{3+} 2-μm modelocking at 80 mW of power. A scaled up version of this scheme was shown by others to achieve excellent frequency conversion throughout the mid-IR without damage.

The development of techniques to periodically pole ferroelectric materials such as lithium niobate and RTA and use them in quasi-phasematching revolutionized nonlinear frequency conversion. Dr Larry Myers set up a poling station in our lab [the only one in a DoD lab] for this program and we extensively studied and advanced the state of the art in this area. We demonstrated > 1 W output at 4 μm with 9 W of 1-μm cw pumping. We demonstrated discrete and continuous tuning over the 1.5-4 μm range using periodically poled lithium niobate [PPLN] wafers fabricated with engineered templates. We demonstrated broadband emission using fan gratings. We demonstrated electric-field controlled frequency tuning of a PPLN OPO. This PPLN frequency conversion technology has transitioned to industry and is currently in production for military IRCM systems.

We also investigated techniques to scale up the pulse energy in PPLN OPOs for burst illumination laser radar applications. By using stacks of PPLN wafers pumped by Nd:YAG beamlets, we were able to achieve 60 mJ/pulse in a 3-ns pulse at the “eyesafe” wavelength of 1.5 μm. We also showed that high pulse energies can be seeded in PPLN for the narrowband operation needed for spectroscopy and remote sensing.

Other materials were investigated for their amenability to poling and their nonlinear conversion performance. We successfully poled RTA and demonstrated pulsed OPO/OPG (optical parametric generation) operation with it. While RTA has a higher damage threshold than PPLN, it is much more expensive and cannot be made into large (e.g. 3” diameter) wafers like PPLN.

Most of our work with poled ferroelectrics was done with congruent lithium niobate. Recently crystal growers have been able to grow stoichiometric lithium niobate. Stoichiometric material has less defects and thus poles with a lower poling voltage. We performed a direct comparison measurement by periodically poling stoichiometric $LiTaO_3$ (PPLT) and both stoichiometric and congruent $LiNbO_3$ and placing samples in an optical parametric generation setup. These materials had comparable performance in terms of slope efficiency and output bandwidth, and thresholds proportional to the inverse-square of the effective nonlinear coefficient. Idler wavelengths as long as 5 microns were obtained, but their output power was limited by material absorption. Questions remain about the uniformity of crystalline structure in the stoichiometric materials so congruent lithium niobate is still the low risk choice for systems use right now.

Frequency conversion is not the only use for periodically poled materials. In collaboration with Pennsylvania State University (PSU), we investigated PPLT for electro-optic beam steering. A computer-controlled 5-stage PPLT EO beam steering device demonstrated 10^o of beam steering. We also demonstrated a device format that can be scaled to high power operation at any wavelength transparent to PPLT.

We investigated the optical properties and nonlinear performance of optically patterned GaAs (OPGaAs). This material is of interest because it is transparent throughout the 1-14 μm range and has a nonlinear coefficient even higher than lithium niobate. But this material must be grown with a pattern built in and cannot be poled. OPGaAs fabrication is currently being developed under another Air Force program. While OPO operation has been achieved by others, we have found materials to be highly variable in their transmission and domain fidelity. Additional fabrication development is needed but this material could be very important for full mid-IR wavelength coverage and 8-12 μm IR coverage as well.

For further details on any of the results discussed above please refer to the publications generated under this effort and listed chronologically in Section 4.

3. CONCLUSIONS AND FURTHER RESEARCH

This effort was instrumental in the development of tunable solid-state infrared lasers useful for IRCM, laser radar, and remote sensing. Materials like periodically poled lithium niobate and devices like bow-tie optical parametric resonators are being fielded in the real world. Other devices and techniques like Cr^{2+} lasers and patterned GaAs frequency converters will find their place in military and commercial applications as the technologies mature.

However, the job is far from complete. EO sensor users continue to push for more power, agile wavelengths, modifiable waveforms, multifunctionality, more reliability, reduced cost and smaller size. In fact, the development of lasers for sensor applications has become more of a program to smoothly integrate the entire transmitter into a platform. A functionally flexible system with conformability to platform surfaces and volumes is needed for next generation EO sensor systems.

Recent advances in fiber lasers, holey photonic fibers for optical transport and novel quasi-phasematched materials make a multi-port source with no free-space optics and broadband tunability a possibility. Such a system would be able to direct the right wavelength and waveform to the right aperture on any aircraft. A new in-house effort is needed and is being planned to develop the next generation of active EO sources towards this goal.

4. PUBLICATIONS

Listed below are the publications that were generated under this effort. These publications, in chronological order, should be consulted for a detailed account of the many accomplishments achieved and discussed in Section 2 above.

4.1 Journal Publications:

C. L. Marquardt, D. G. Cooper, P. A. Budni, M. G. Knights, K. L. Schepler, R. DeDomenico, and G. C. Catella, "Thermal lensing in silver gallium selenide parametric oscillator crystals," *Appl Opt* **33**, (1994) 3192-3197.

R. D. Peterson, K. L. Schepler, J. L. Brown, and P. G. Schunemann, "Damage properties of $ZnGeP_2$ at 2 μm," *J Opt Soc Am B* **12,** 2142-2146 (1995).

D. L. Fenimore, K. L. Schepler, U. B. Ramabadran,and S. R. McPherson, "Infrared corrected Sellmeier coefficients for potassium titanyl arsenate," *J Opt Soc Am B* **12,** 794-796 (1995).

D. L. Fenimore, K. L. Schepler, D. Zelmon, S. Kück, U. B. Ramabadran, P. VonRichter, and D. Small, "Rhubidium titanyl arsenate difference frequency generation and validation of new Sellmeier coefficients," *J Opt Soc Am B* **13**, 1935-1940 (1996).

K. L. Schepler, S. Kück, and L. Shiozawa, "Cr^{2+} emission spectroscopy in CdSe," *J Lumin*, **72-74**, 116-117 (1997).

S. Kück, K. L. Schepler, S. Hartung, K. Petermann, and G. Huber, "Excited state absorption and its influence on the laser behavior of Cr^{4+}-doped garnets," *J Lumin*, **72-74**, 222-223 (1997).

S. Kück, K. L. Schepler, and B. H. T. Chai, "Evaluation of Mn^{5+}-doped $Sr_5(VO_4)_3F$ as a laser material based on excited-state absorption and stimulated-emission measurements," *J Opt Soc Am B* **14**, 957-963 (1997).

M. A. Dubinskii, K. L. Schepler, R. Yu. Abdulsabirov, and S.L. Korableva, "All-solid-state injection-seeded tunable ultraviolet laser," *J Modern Opt* **45**, 1993-1998 (1998).

P. G. Schunemann, K. L. Schepler. and P. A. Budni, "Nonlinear conversion performance of $AgGaSe_2$, $ZnGeP_2$, and $CdSeAs_2$," *MRS Bulletin/July 1998*, 45-49 (1998).

M. A. Dubinskii, K. L. Schepler, V. V. Semashko, R. Yu. Abdulsabirov, and S. L. Korableva, "Spectroscopic analogy approach in selective search for new Ce^{3+}-activated all-solid-state tunable ultraviolet laser materials," *J Modern Opt* **45**, 221-226 (1998).

M. J. Missey, V. Dominic, P. E. Powers, and K. L. Schepler, "Periodically poled lithium niobate monolithic nanosecond optical parametric oscillators and generators," *Opt Lett* **24**, 1227-1229 (1999).

Jason McKay, Kenneth L. Schepler, and Gary Catella, "Efficient grating-tuned mid-IR Cr^{2+}:CdSe laser," *Opt Lett* **24**, 1575-1577 (1999).

N. O'Brien, M. Missey, P. Powers, V. Dominic, and K. L. Schepler, "Electro-optic spectral tuning in a continuous-wave, asymmetric-duty-cycle, periodically poled $LiNbO_3$ optical parametric oscillator," *Opt Lett* **24**, 1750-1752 (1999).

Monte D. Turner, Won B. Roh, and Kenneth L. Schepler, "Nonlinear properties of GaSb and GaInAsSb and their application for phase conjugation in degenerate four-wave mixing," *J. Opt. Soc. Am. B* **17**, 790-804 (2000).

M. Missey, S. Russell, V. Dominic, R. Batchko, and K. L. Schepler, "Real-time visualization of domain formation in periodically poled lithium niobate," *Optics Express* **6**, 186-195 (2000).

Stephen M. Russell, Peter E. Powers, Mark J. Missey, and Kenneth L. Schepler, "Broadband mid-infrared generation with two-dimensional quasi-phase-matched structures," *IEEE J. of Quantum Electron*. **37**, 877-887 (2001).

D. A. Scrymgeour, L. Tian, V. Gopalan, D. Chauvin, and K. L. Schepler, "Phased-array electro-optic steering of large aperture laser beams using ferroelectrics," *Appl. Phys. Lett.,* **86**, *211113* (2005).

P. E. Powers, P. K. Bojja, R. Alkuwari, E. Vershure, and K. L. Schepler, "High energy seeded optical parametric generation with elliptical beams in quasi-phase-matched crystals," submitted to *Journal of the Optical Society of America.*

K. L. Schepler, R. D. Peterson, P. A. Berry, and J. B. McKay, "Thermal effects in Cr^{2+}:ZnSe thin disk lasers," submitted to *IEEE Journal of Quantum Electronics.*

4.2 Conference Publications

Dale L. Fenimore, Kenneth L. Schepler, and Uma B. Ramabadran, “Improved Sellmeier coefficients for potassium titanyl arsenate, $KTiOAsO_4$ (KTA),” 1994 OSA Annual Meeting, Oct. 1994, Paper TuW4.

K. L. Schepler, B. D. Smith, and F. Heine, “A Completely Solid-State Mode-Locked 2-Micrometer Laser,” *Laser Tech Briefs* **2**, (1994) 40-41.

K. L. Schepler, B. D. Smith, F. Heine, and P. A. Budni, “Mode Locking of Diode-Pumped Tm,Ho:YLF,” *OSA Proceedings on Advanced Solid-State Lasers*, Tso Yee Fan and Bruce H. T. Chai, eds. (Optical Society of America, Washington, DC 1994), **Vol 20**, 257-259.

R. D. Peterson, K. L. Schepler, J. L. Brown, and P. G. Schunemann, “Robust damage thresholds in $ZnGeP_2$ at 2 µm,” in *Conference on Lasers and Electro-Optics*, **Vol. 15**, 1995 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1995), p. 245.

Uma. B. Ramabadran, Dale. L. Fenimore, David E. Zelmon, David Small, Paul Von Richter, and Kenneth L. Schepler, “Improved phase matching predictions based on mid-ir dispersion data for rubidium titanyl arsenate (RTA),” 1995 OSA Annual Meeting (Optical Society of America, Washington, D.C., 1995), p. 105.

S. Kück, K. L. Schepler, K. Petermann, and G. Huber, “Excited state absorption and stimulated emission measurements of Cr^{4+}-doped $Y_3Al_5O_{12}$, $Y_3Sc_{0.9}Al_{4.1}O_{12}$, and $CaY_2Mg_2Ge_3O_{12}$” *OSA Trends in Optics and Photonics on Advanced Solid-State Lasers*, Stephen A. Payne and Clifford R. Pollock, eds. (Optical Society of America, Washington D.C., 1996), **Vol. 1**, pp. 94-96.

S. Kück, K. L. Schepler, S. Hartung, K. Petermann, and G. Huber, “Mn^{3+} as a potential laser ion: The role of excited state absorption and crystal field strength,” International Quantum Electronics Conference ‘96, Sydney, Australia.

S. Kück, K. L. Schepler, S. Hartung, K. Petermann, and G. Huber, “Excited state absorption and its influence on the laser behavior of Cr^{4+}-doped garnets,” International Conference on Luminescence, ‘96, Prague, Czech Republic.

M. D. Turner, W. B. Roh, and K. L. Schepler, “Degenerate four-wave mixing at 2.1 µm in Gallium Antimonide with a Cr,Tm,Ho:YAG laser,” in *Advanced Solid-State Lasers,* Technical Digest (Optical Society of America, Washington D.C., 1997), pp. 48-50.

M. A. Dubinskii, K. L. Schepler, A. K. Naumov, V. V. Semashko, R. Yu. Abdulsabirov, and S. L. Korableva, “New low-threshold laser for diode pumping based on $Nd^{3+}:KY_3F_{10}$,” in *Advanced Solid-State Lasers,* Technical Digest (Optical Society of America, Washington D.C., 1997), pp. 183-185.

M. A. Dubinskii, K. L. Schepler, V. V. Semashko, R. Yu. Abdulsabirov, B. M. Galjautdinov, S. L. Korableva, and A. K. Naumov, "Ce^{3+}:$LiBaF_3$ as new prospective active material for tunable UV laser with direct pumping," in *Advanced Solid-State Lasers*, Technical Digest (Optical Society of America, Washington D.C., 1997), pp. 349-351.

M. A. Dubinskii, K. L. Schepler, R. Yu. Abdulsabirov, V. V. Semashko, A. K. Naumov, and S.L. Korableva, "New prospective medium for tunable UV lasing with quadrupled Nd-laser pumping," in *Conference on Lasers and Electro-Optics*, Vol. **6**, 1998 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1998) p. 183.

M. A. Dubinskii, K. L. Schepler, A. K. Naumov, V. V. Semashko, R. Yu. Abdulsabirov, and S.L. Korableva, "Tunable cw Nd laser with end diode pumping for remote environmental monitoring," in *Conference on Lasers and Electro-Optics*, Vol. **6**, 1998 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1998) p. 546.

M. A. Dubinskii, K. L. Schepler, R. Yu. Abdulsabirov, and S.L. Korableva, "Tunable UV Ce:LiCAF injection-seeded laser for high spectral brightness applications," *OSA Trends in Optics and Photonics, Vol.* **19**, Advanced Solid State Lasers, Walter R. Bosenberg and Martin M. Fejer, eds. (Optical Society of America, Washington, DC 1998), pp. 6-9.

Jason McKay, Kenneth L. Schepler, and Stefan Kück, "Chromium (II): cadmium selenide laser," 1998 OSA Annual Meeting, Oct. 1998, Paper ThGG1.

M. A. Dubinskii, K. L. Schepler, R. Yu. Abdulsabirov, V. V. Semashko, A. K. Naumov, and S.L. Korableva, "Nd^{3+}:YF_3 as a laser material for cw diode pumped operation," *OSA Trends in Optics and Photonics, Vol. **26***, Advanced Solid State Lasers, Martin M. Fejer, Hagop Injeyan and Ursula Keller, eds. (Optical Society of America, Washington, DC 1999), pp. 303-305.

Jason McKay, Kenneth L. Schepler, and Gary Catella, "Kilohertz 2.6-μm Cr^{2+}:CdSe laser," *OSA Trends in Optics and Photonics, Vol. **26***, Advanced Solid State Lasers, Martin M. Fejer, Hagop Injeyan and Ursula Keller, eds. (Optical Society of America, Washington, DC 1999), pp. 420-426

Jason McKay, Kenneth L. Schepler, and Gary Catella, "Broadly tuned, all-solid-state, Cr^{2+}:CdSe mid-IR laser," in *Conference on Lasers and Electro-Optics*, 1999 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1999) pp. 547-548.

Kenneth L. Schepler, Mark J. Missey, Ned O'Brien, and Peter Powers, "Power and energy scaling for quasi-phasematched OPOs," in *Operational Characteristics and Crystal Growth of Nonlinear Optical Materials*, Ravindra B. Lal, Donald O. Frazier, eds., Proceedings of SPIE Vol. **3793**, pp. 187-195.

Jason McKay, Debra Krause and Kenneth L. Schepler, "Optimization of Cr^{2+}:CdSe for efficient laser operation," *OSA Trends in Optics and Photonics Vol **34**, Advanced Solid-State Lasers*, Hagop

Injeyan, Ursula Keller, and Christopher Marshall, eds. (Optical Society of America, Washington, D.C., 2000) pp. 218-224.

Jason McKay, Debra Krause, and Kenneth L. Schepler, "Mitigation of bleaching in a Cr^{2+}:CdSe laser," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, Washington, D.C., 2000) p. 453.

Steve Russell, Mark J. Missey, Peter Powers, and Kenneth L. Schepler, "Periodically poled lithium niobate with a 20^{o} fan angle for continuous OPG tuning," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, Washington, D.C., 2000) pp. 632-633.

Stephen M. Russell, Mark J. Missey, Peter E. Powers, and Kenneth L. Schepler, "Optical parametric generation of greater than 30 mJ signal energies in PPLN stacks," Postdeadline Paper CPD24 in *Conference on Lasers and Electro-Optics* (Optical Society of America, Washington, DC, 2001).

Stephen M. Russell, Mark J. Missey, Peter E. Powers, and Kenneth L. Schepler, "Broadband mid-infrared generation in elliptically pumped periodically poled lithium niobate devices," in *Conference on Lasers and Electro-Optics* (Optical Society of America, Washington, DC, 2001) pp. 425-426.

Jason McKay, Won Roh, and Kenneth L. Schepler, "Extended mid-IR tuning of a Cr^{2+}:CdSe laser," *Trends in Optics and Photonics Vol.* ***68***, *Advanced Solid-State Lasers*, M. E. Fermann and L. R. Marshall, eds. (Optical Society of America, Washington, DC 2002) pp. 371-373.

Jason McKay, Won Roh, and Kenneth L. Schepler, "4.2 W Cr^{2+}:ZnSe face cooled disk laser," *Trends in Optics and Photonics Vol. 73, Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, Washington, DC 2002), pp. 119-120.

Peter E. Powers, Prasanth K. Bojja, Eric M. Vershure, and Kenneth L. Schepler, "Narrowband mid-infrared generation in elliptically pumped periodically poled lithium niobate," Paper CThG7 in *Conference on Lasers and Electro-Optics* (Optical Society of America, Washington, DC, 2003) pp. 37-38.

Jason McKay, Won Roh, and Kenneth L. Schepler, "Thermal lensing in Cr^{2+}:ZnSe face-cooled disks," *Trends in Optics and Photonics Vol.* ***83***, *Advanced Solid-State Photonics*, John J. Zayhowski, ed. (Optical Society of America, Washington, DC 2003), pp. 220-223

Rita D. Peterson and Kenneth L. Schepler, "1.9-μm-fiber-pumped Cr:ZnSe laser," presented at *Advanced Solid-State Photonics* in Vienna Austria, Feb 2005 (Optical Society of America).